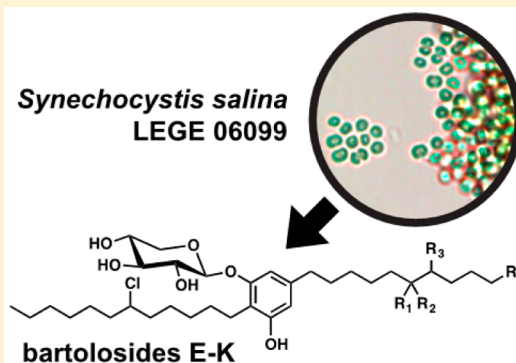


## Bartolosides E–K from a Marine Coccoid Cyanobacterium

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## S Supporting Information

**ABSTRACT:** The glycosylated and halogenated dialkylresorcinol (DAR) compounds bartolosides A–D (1–4) were recently discovered from marine cyanobacteria and represent a novel family of glycolipids, encoded by the *brt* biosynthetic gene cluster. Here, we report the isolation and NMR- and MS-based structure elucidation of monoglycosylated bartolosides E–K (5–11), obtained from *Synechocystis salina* LEGE 06099, a strain closely related to the cyanobacterium that produces the diglycosylated 2–4. In addition, a genome region containing orthologues of *brt* genes was identified in this cyanobacterium. Interestingly, the major bartoloside in *S. salina* LEGE 06099 was 1 (above 0.5% dry wt), originally isolated from the phylogenetically distant filamentous cyanobacterium *Nodosilinea* sp. LEGE 06102. Compounds 5–11 are analogues of 1, with different alkyl chain lengths or halogenation patterns. Their structures and the organization of the *brt* genes suggest that the DAR-forming ketosynthase BrtD can generate structural diversity by accepting fatty acyl-derived substrates of varying length. Compound 9 features a rare midchain gem-dichloro moiety, indicating that the putative halogenase BrtJ is able to act twice on the same midchain carbon.



Glycolipids are abundant in cyanobacteria and are present as a functionally relevant component of photosystem I,<sup>1</sup> in thylakoid and cytoplasmic membranes where they have a structural role<sup>2</sup> that is also related to thermotolerance,<sup>3</sup> and in the heterocytes, creating a barrier to maintain an anoxic environment.<sup>4</sup> Recently, we have uncovered a new class of glycolipids from marine cyanobacteria: bartolosides A–D (1–4), which are mono- or diglycosylated dialkylresorcinols (DARs) with halogenated alkyl moieties.<sup>5</sup> The diglycosylated bartolosides 2–4, produced by the coccoid cyanobacterium *Synechocystis salina* LEGE 06155, feature O-linked  $\alpha$ -L-rhamnose and C-linked  $\beta$ -xylose, while the monoglycosylated 1 produced by *Nodosilinea* sp. LEGE 06102 has an O-linked  $\beta$ -D-xylosyl moiety. The biosynthesis of the DAR skeleton of 2–4 involves first the head-to-head condensation of an  $\alpha,\beta$ -unsaturated fatty acyl-ACP thioester with a  $\beta$ -keto-fatty acyl-ACP thioester (abundant fatty acyl derivatives in cyanobacterial cells), catalyzed by the ketosynthase BrtD. This is followed by oxidative aromatization, catalyzed by the FMN-dependent aromatase BrtC.<sup>5</sup> Other functions encoded in the bartoloside biosynthetic gene cluster (*brt*) include glycosyltransferases, a putative halogenase

(BrtJ), and a glycolipid export cassette.<sup>5</sup> In assays using human cancer cell lines, 1 and 2 showed low to mid micromolar cytotoxicity.<sup>5</sup>

As part of a bioassay-guided marine biodiscovery effort, we have followed a cytotoxic midpolarity fraction from one other *S. salina* strain (LEGE 06099) and isolated 1 as a major metabolite, together with the seven minor monoglycosylated bartolosides E–K, 5–11. We report here on the structure elucidation and biological activity of these compounds. Moreover, a putative *brt* gene cluster was identified in the genome of *S. salina* LEGE 06099, and the biosynthesis of mono- and diglycosylated bartolosides is discussed.

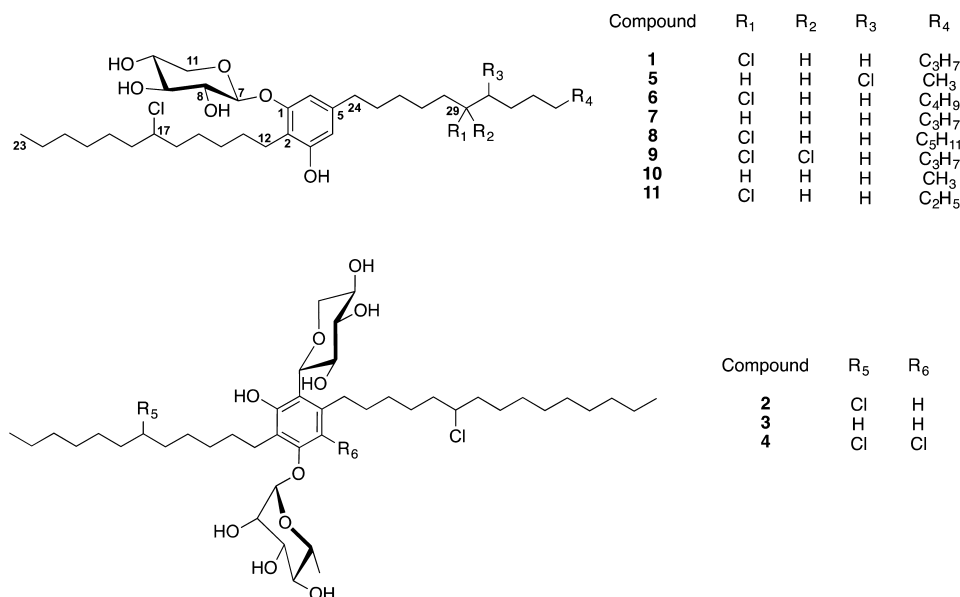
## RESULTS AND DISCUSSION

**Isolation and Structure Elucidation of Monoglycosylated Bartolosides from *S. salina* LEGE 06099.** The marine cyanobacterium *S. salina* LEGE 06099, isolated from the intertidal

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Chart 1



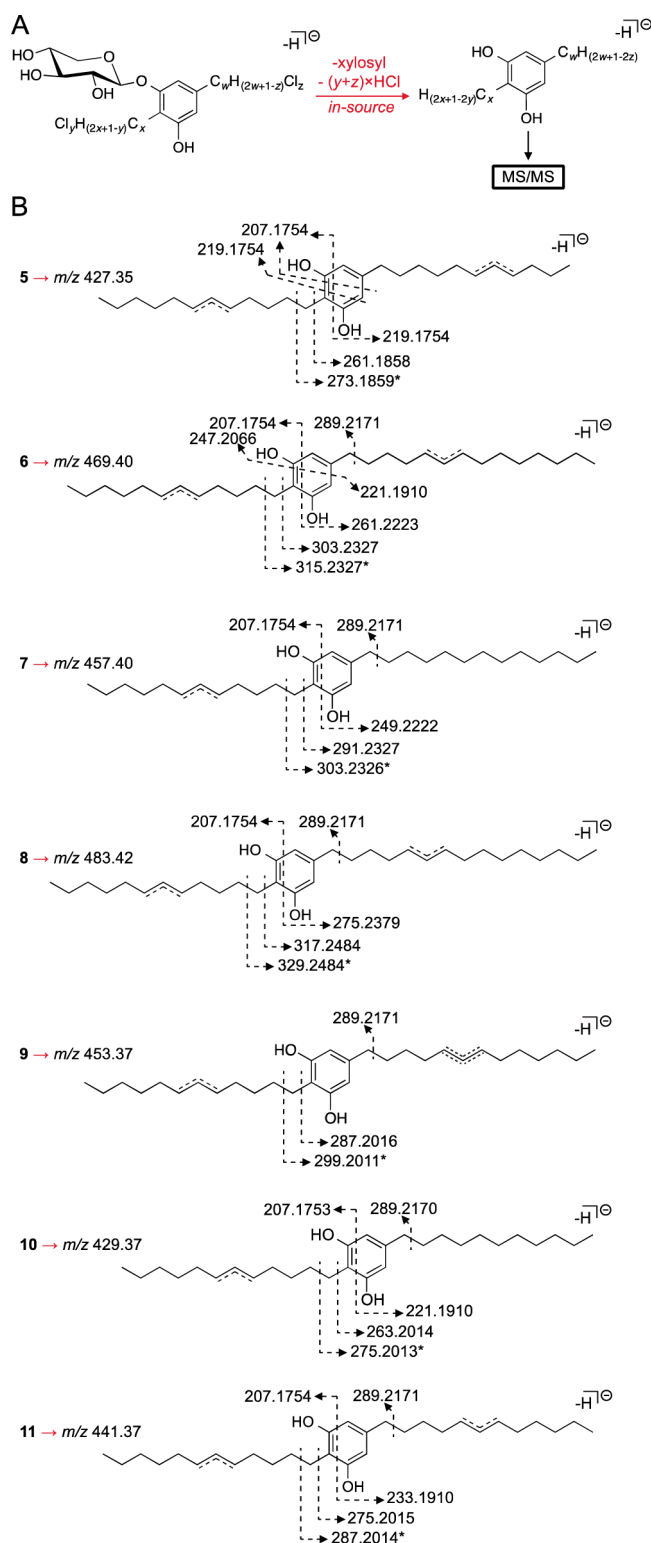
zone of a rocky beach in Northern Portugal,<sup>6</sup> was grown in multiple 4 L cultures. The corresponding biomass was harvested by centrifugation and fractionated using vacuum liquid chromatography (VLC). One of the resulting fractions, eluting with EtOAc/Hex, 4:1 (v/v), showed cytotoxic activity against the MG-63, RKO, and T47D human cancer cell lines. Further fractionation by normal-phase gravity column chromatography and reversed-phase HPLC yielded pure **1** as a major metabolite, along with **5** and other minor metabolites, which showed MS patterns consistent with chlorination. The identity of **1** was established based on identical NMR, MS fragmentation, and sugar configuration data of the metabolite isolated from *S. salina* LEGE 06099 and of **1** isolated from *Nodosilinea* sp. LEGE 06102 (Figure S1, Figure S2, Table S1, [Supporting Information](#)).<sup>5</sup> In order to obtain the minor metabolites in sufficient amounts for detailed structural characterization, *S. salina* LEGE 06099 was grown in a larger scale, ultimately yielding **1** (164 mg, 0.58% d.w.), as well as the minor constituents **6**–**11**.

In our previous work with **1**–**4**, elucidation of the planar structures, especially of the chlorinated DAR skeleton, required an integration of NMR, MS<sup>n</sup> data, and biosynthetic information.<sup>5</sup> In particular, HSQC-TOCSY experiments were instrumental for the assignment of the chlorinated positions, MS data informed on the alkyl chain lengths, while an understanding of which fatty acid derivatives were involved in the biosynthesis clarified the relative positions of the alkyl chains. Hence, as a general strategy to elucidate the structures of **5**–**11**, we used such previous information on **1**–**4** as a reference for comparison. All of the bartolosides herein reported contain a xylosyl moiety. Given the identical NMR data for this portion of the molecules with that of **1**, we propose that this residue is  $\beta$ -D-xylopyranosyl for **5**–**11** as determined for **1**.<sup>5</sup>

Metabolite **5** was found to have the molecular formula C<sub>34</sub>H<sub>58</sub>Cl<sub>2</sub>O<sub>6</sub> on the basis of HRESIMS data, two carbons and four protons less than compound **1**. Analysis of <sup>1</sup>H and <sup>13</sup>C APT NMR data in DMSO-*d*<sub>6</sub> quickly revealed that the sugar and aromatic regions were identical to those in **1**. Furthermore, no additional methyl or methine carbon resonances were found for **5**, compared to **1**. This indicated that the differences

between the two compounds are two alkyl chain methylenes; to clarify where these differences were found, we resorted to HRESIMS<sup>n</sup> analysis of a dehalogenated, aglycone species formed in the ionization chamber, as previously observed for **1**–**4**.<sup>5</sup> Fragmentation of this species revealed that a C<sub>10</sub> chain was present as a substituent in position 5 of the resorcinol ring (Figure 1, Figure S3). Closer inspection of the <sup>13</sup>C NMR data for the two compounds revealed that only three methylene carbons resonating at  $\sim \delta_C$  26.0–25.6 were found in **5**, compared to the four methylenes C-15, C-19, C-27, and C-31 in **1**. Concomitantly, one of the methylenes vicinal to the chlorinated position in **5** was slightly more shielded ( $\delta_C$  37.5) when compared to **1**. In addition, while for **1** two  $\omega$ -3 carbon resonances at  $\delta_C$  31.1 and 30.7 are observed, in **5** a single  $\omega$ -3 carbon resonates in this region. One of the  $\omega$ -2 carbon signals is also more shielded in **5** ( $\delta_C$  21.7;  $\delta_C$  22.0 for **1**). This hinted that the chlorinated methine was closer to the chain terminus in **5** when compared to **1**. HMBC correlations connecting one of the slightly resolved methyl triplets to both an  $\omega$ -3 carbon resonating at  $\delta_C$  28.1 (C-32) and an  $\omega$ -2 carbon resonating at  $\delta_C$  21.7 (C-33) supported that chlorination in this chain would be in position  $\omega$ -5 (Figure 2), thereby establishing the planar structure of compound **5**. Of practical importance, the structure elucidation of **5** also clarified that, in **1**, the  $\omega$ -3 carbons in the C<sub>12</sub> and C<sub>13</sub> chains resonate at  $\delta_C$  30.7 and 31.1, respectively (in DMSO-*d*<sub>6</sub>).

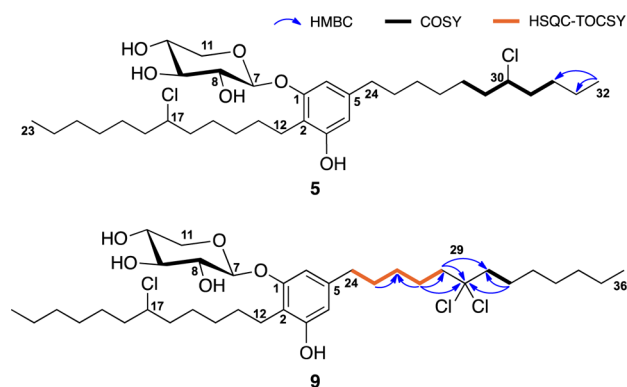
Metabolite **6** was found to have the molecular formula C<sub>37</sub>H<sub>64</sub>Cl<sub>2</sub>O<sub>6</sub> based on HRESIMS analysis, corresponding to one additional carbon and two protons, when compared to **1**. Comparison of 1D and 2D NMR data (including HSQC-TOCSY) for **6** and **1** did not reveal discernible differences, except for an additional peak in the  $\delta$  28.5–28.4 region in the spectrum of **6**, suggesting that an extra aliphatic methylene would be present in this compound. A smaller additional peak in the <sup>13</sup>C APT spectrum of **6** at  $\delta$  31.1 was also observed, but it lacked clear HSQC or HMBC correlations and was not considered. HRESIMS<sup>n</sup> analysis of the in-source-isolated dechlorinated aglycone of **6** showed that the additional methylene was present in the C-5 alkyl chain substituent (Figure 1, Figure S3). The positioning of the Cl atom in this chain is presumed to be at a six-carbon distance from the



**Figure 1.** HRESIMS<sup>n</sup> analysis of 5–11. (A) For each compound, an in-source-formed dechlorinated aglycone species was fragmented to provide information on the length and number of halogens of each alkyl chain. (B) Annotation of diagnostic  $m/z$  values encountered in the MS/MS analysis for each species. Asterisks indicate tropolone formation following fragmentation.

resorcinol ring, due to the highly similar 1D and 2D NMR data (in particular HSQC-TOCSY) of 6 and 1.

The HRESIMS-derived molecular formula of metabolite 7 ( $C_{36}H_{63}ClO_6$ ) suggested that this compound could be an



**Figure 2.** Key 2D NMR correlations supporting the proposed chlorine position in the C-5 alkyl substituent for metabolites 5 and 9.

analogue of 1 with a fully aliphatic alkyl chain. In fact, the  $^1H$  NMR data confirmed this hypothesis, with the multiplets for the chlorinated methine and vicinal methylenes in 7 integrating for one and four protons, respectively. This was in agreement with the  $^{13}C$  APT data, with a single carbon resonance at  $\delta_C$  64.8 for a chlorinated methine and two carbon resonances at  $\delta_C$  37.9–37.8 for the vicinal positions. Less shielded resonances of the methylene vicinal to the benzylic position (C-25) in the  $C_{13}$  chain ( $\delta_C$  30.7 in 7 and  $\delta_C$  30.6 in 1) and one of the  $\omega$ -3 carbons ( $\delta_C$  31.3 in 7 and  $\delta_C$  31.1 in 1) formed the basis for our proposal for a nonhalogenated  $C_{13}$  chain in 7, which is supported by HRESIMS<sup>n</sup> analysis (Figure 1, Figure S3).

Metabolite 8 was found to have the molecular formula  $C_{38}H_{66}Cl_2O_6$  from the HRESIMS data, corresponding to two additional carbons and four protons when compared to 1. No important differences in the resonances for the aromatic and xylose residue regions between 8 and 1 were found in  $^1H$  and  $^{13}C$  APT data, nor were additional methyl or methine resonances found for 8, consistent with two extra methylenes in the alkyl chains of this compound when compared to 1. Overall, 1D and 2D (including HSQC-TOCSY) NMR data for 8 were highly similar to those for 1, with the exception of a more complex aliphatic methylene region in the carbon spectrum of 8, as expected. A good agreement with the  $^{13}C$  data ( $\delta_C$  38.0–13.5 region) for 2<sup>5</sup> led us to hypothesize that  $C_{12}/C_{15}$  alkyl chains would be present in 8, which was confirmed by HRESIMS<sup>n</sup> fragmentation analysis of the in-source-formed dechlorinated aglycone of 8 (Figure 1, Figure S3). Given the similar HSQC-TOCSY data of 8 and 1 in establishing the connection from the benzylic position (C-/H<sub>2</sub>-24) to the chlorinated methine (C-/H-29) (Figure S4), a  $\omega$ -10 positioning of the Cl atom was assigned for 8.

Metabolite 9 was found to have the molecular formula  $C_{36}H_{61}Cl_3O_6$  on the basis of HRESIMS data, consistent with an analogue of 1 bearing an additional chlorine atom. The  $^1H$  and  $^{13}C$  APT NMR data in DMSO- $d_6$  of 9 showed resonances for the aromatic and sugar moieties mostly identical to those of 1, although slight (<0.03 ppm) differences were observed for the sugar and resorcinol exchangeable protons. Integration of the chlorinated methine multiplet resonating at  $\delta_H$  4.01 indicated that this corresponded to a single proton, which would be consistent with a *gem*-dichloro group in the molecule. A multiplet integrating for four protons at  $\delta_H$  2.19 (H<sub>2</sub>-28/H<sub>2</sub>-30) with an HSQC correlation to two carbons at  $\delta_C$  47.2–47.1 was found to have no counterpart in the NMR data of 1. A nonprotonated carbon ( $\delta_C$  97.2, C-29) was HMBC-correlated to the  $\delta_H$  2.19 multiplet, which in turn showed a COSY correlation to a



multiplet at  $\delta_{\text{H}}$  1.57. An HSQC experiment allowed assignment of this resonance to two methylene carbons ( $\delta_{\text{C}}$  24.8, 24.5, C-27/31). These protons were strongly correlated to the C-29 and C-28/30 positions. Overall, this established a midchain *gem*-dichloro moiety. HSQC-TOCSY revealed that the H<sub>2</sub>-24 ( $\delta_{\text{H}}$  2.40) and the H<sub>2</sub>-28 protons were correlated to C-25 ( $\delta_{\text{C}}$  30.7), while the H<sub>2</sub>-27 ( $\delta_{\text{H}}$  1.57) and H<sub>2</sub>-28 protons were correlated to C-26 ( $\delta_{\text{C}}$  28.2), placing the *gem*-dichloro group on the 5-alkyl substituent (Figure S5). HRESIMS<sup>n</sup> analysis supported this assignment and indicated that the two alkyl chains were C<sub>12</sub> and C<sub>13</sub> (Figure 1, Figure S3). The exact positioning of the *gem*-dichlorinated position was established from the aforementioned HSQC-TOCSY data, from the COSY correlations of both the H<sub>2</sub>-25 ( $\delta_{\text{H}}$  1.50) and H<sub>2</sub>-27 protons to H<sub>2</sub>-26 ( $\delta_{\text{H}}$  1.31), and from HMBC correlations between C-26 and both H<sub>2</sub>-25 and H<sub>2</sub>-27 (Figure 2, Figure S5). Selective 1D TOCSY experiments with varying mixing times supported these assignments, as the magnetization from both H<sub>2</sub>-24 and H<sub>2</sub>-28 is propagated to a  $\delta_{\text{H}}$  1.31-centered multiplet (H<sub>2</sub>-26), through H<sub>2</sub>-25 and H<sub>2</sub>-27, respectively (Figure S5).

From HRESIMS analysis, metabolite **10** was found to have the molecular formula C<sub>34</sub>H<sub>59</sub>ClO<sub>6</sub>. Due to the low amount of compound isolated (0.2 mg), we were unable to obtain a <sup>13</sup>C spectrum, and both the HMBC and HSQC-TOCSY data showed limited correlational information. The molecular formula indicated that **10** could be a shorter chain analogue of **1** with just one chlorination. This possibility was corroborated by the identical <sup>1</sup>H NMR data in DMSO-*d*<sub>6</sub> for the aromatic and sugar regions of **10** and **1** and by integrations of one and four protons for the signals corresponding to the chlorinated methine and vicinal methylenes, respectively, in **10**. Further structural details were obtained from HRESIMS<sup>n</sup> analysis. Because only one chlorination is present, the dehalogenated aglycone isolated in the ionization chamber that was subject to fragmentation contained an unsaturation in only one of the chains (loss of HCl) (Figure 1, Figure S3). We could therefore infer chain lengths from the MS data, as well as which of the two chains contained the unsaturation. The alkyl chain substituent at C-5 was thus found to be fully aliphatic and two carbons shorter than the corresponding alkyl chain in **1** (Figure 1, Figure S3).

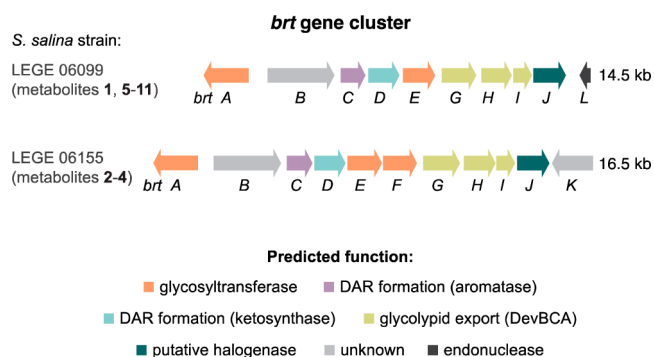
Metabolite **11** was found to have the molecular formula C<sub>35</sub>H<sub>60</sub>Cl<sub>2</sub>O<sub>6</sub> from HRESIMS analysis, with one CH<sub>2</sub> formula difference compared to **1**. The <sup>1</sup>H and <sup>13</sup>C APT NMR data in DMSO-*d*<sub>6</sub> for **11** and **1** were highly similar, indicating that compound **11** should have one less alkyl chain methylene. HRESIMS<sup>n</sup> analysis of **11** was used for further structural inferences. Fragmentation of the respective in-source-isolated dehalogenated aglycone species clarified that a C<sub>12</sub> chain was a substituent at position 5 of the resorcinol ring (Figure 1, Figure S3). Given the similarity in the NMR data, the positioning of the Cl atom is proposed from the conserved halogenation pattern observed in the bartolosides (six-carbon distance from the aromatic ring, exception is compound **5**).

The availability of NMR and MS data for **1**–**4** greatly facilitated the structure elucidation of bartolosides **5**–**11**. Still, the precise positioning of the Cl atom in the C-5 alkyl substituent was only evident for compounds **5** and **9**. For compounds **6**, **8**, and **11**, such positioning is in agreement with our elucidations of **1**–**4**.<sup>5</sup> From our proposed structures, the chlorination on the C-5 substituent in **5** occurs in a different position than for all other bartolosides (seven carbons away from the resorcinol ring vs six carbons, respectively), suggesting that BrtJ is capable of acting on different positions. However,

the pronounced chemical shift degeneracy for the aliphatic methylenes that are more than two carbons away from the chlorine atom moiety renders Cl positions in both alkyl chains difficult to differentiate from NMR (including HSQC-TOCSY) data. Therefore, structural confirmation of the proposed bartoloside structures by total synthesis is highly desirable (also for establishing the absolute configurations), since these compounds have eluded all of our crystallization attempts.

#### Biosynthesis of Bartolosides in *S. salina* LEGE 06099.

While the two bartoloside-producing *S. salina* strains are phylogenetically close (Figure S6), we could not find **2**–**4** in an organic extract of *S. salina* LEGE 06099, nor could we find **1** or **5**–**11** in an extract of *S. salina* LEGE 06155 (Figure S6). To clarify how these observations translated at the genetic level and how the structural diversity observed in the compounds isolated from *S. salina* LEGE 06099 could be generated, we studied the biosynthesis of the bartolosides in this strain. Naturally, we envisioned that its genome would likely harbor a gene cluster with homology to the diglycosylated bartoloside-generating *brt* cluster in *S. salina* LEGE 06155. To obtain stronger evidence for this hypothesis prior to genome sequencing, we used a degenerate PCR strategy to show that *brtC* and *brtD* homologues were indeed found in the genome of *S. salina* LEGE 06099, by obtaining an amplicon that spanned both genes (Figure S8, 82% identity to *brtCD* in *S. salina* LEGE 06155). Following genome sequencing and mining, we were able to identify what, in all likelihood, is the *brt* gene cluster in this cyanobacterium (Figure 3). As expected, the cluster is



**Figure 3.** Overview of the *brt* gene clusters in *S. salina* strains LEGE 06099 and LEGE 06155.

highly homologous to the *S. salina* LEGE 06155 *brt* cluster (Figure 3, Table S2). However, only two glycosyltransferases are encoded in the putative *brt* cluster from *S. salina* LEGE 06099, as opposed to three such enzymes coded by the *S. salina* LEGE 06155 cluster. Given the strong homology between the glycosyltransferases that are shared by both clusters, it is unclear whether the two enzymes play a role in the installation of a single sugar moiety.

A putative halogenase (BrtJ) is present in the two *brt* clusters. Genes homologous to *brtJ* have recently been found in cyanobacterial biosynthetic gene clusters encoding halogenated natural products,<sup>7,8</sup> and bioinformatics analyses have strongly suggested that these enzymes are a new type of dimetal halogenase.<sup>5,7</sup> In *S. salina* LEGE 06099 BrtJ is therefore likely to carry out the single halogenations on unactivated carbons found in all bartolosides, but also to give rise to the *gem*-dichloro group in **9**. This functionality is relatively rare, being found in the cyanobacterial natural products hectochlorin,<sup>9</sup> lyngbyabellins,<sup>10,11</sup>

cyclophanes,<sup>12</sup> and columbamide B,<sup>7</sup> in the myxobacterial metabolite chlorotoni A,<sup>13</sup> and in a handful of marine-derived lipids.<sup>14</sup> In hectochlorin biosynthesis halogenation is carried out by a nonheme iron  $\alpha$ -ketoglutarate-dependent enzyme (HctB),<sup>15</sup> while a FAD-dependent halogenase (CtoA) is thought to install the Cl atoms found in chlorotoni A.<sup>16</sup> Notably, in recent investigations of columbamide B and carbamidocyclophane biosyntheses, terminal *gem*-dichlorination has been suggested to be performed by BrtJ homologues (ColD/ColE and CabC, respectively).<sup>7,17</sup>

Bartoloside A (**1**) is very abundant in *S. salina* LEGE 06099, making up to 0.6% of the total dry weight (d.w.). Such levels are comparable in magnitude to those of lipopolysaccharides in different cyanobacteria cells (0.1–3%, d.w.),<sup>18,19</sup> suggesting that bartolosides may have a structural role. Bartolosides E–K (**5**–**11**) are much less abundant than bartoloside A (**1**) in *S. salina* LEGE 06099 cells. The structural diversity that the *brt* pathway can generate in this strain is, nevertheless, noteworthy. While some of the bartolosides are likely pathway intermediates (i.e., those with a single halogenation, **7** and **10**), shorter or longer chain analogues indicate some relaxed specificity in DAR formation. Previously, we have shown that BrtD accepts even-chain fatty acyl-ACP derivatives—intermediates in fatty acid metabolism—to form the DAR core of **2**–**4**.<sup>5</sup> According to the proposed biosynthesis of the bartolosides,<sup>5</sup> compounds **6** and **11** would result from the BrtD-catalyzed condensation of odd-chain  $\alpha,\beta$ -unsaturated fatty acyl-ACP thioesters ( $C_{17}$  and  $C_{15}$ , respectively) with a 3-oxo-hexadecanoyl-ACP thioester. However, neither odd-chain fatty acids nor their  $\alpha,\beta$ -unsaturated fatty acyl-ACP thioesters are known to be present in cyanobacteria cells.<sup>20</sup> The closely related cyanobacterium *Synechocystis* sp. PCC 6803 is known to be able to synthesize full-length odd-chain (up to  $C_{19}$ ) saturated and unsaturated fatty acids but only when fed with heptanoic acid.<sup>21</sup> The fatty acid biosynthesis machinery of this cyanobacterium can thus elongate odd-chain precursors and generate also odd-chain  $\alpha,\beta$ -unsaturated fatty acyl-ACP thioesters. The intriguing origin of the DAR cores of **6** and **11** in *S. salina* LEGE 06099 will be the subject of further study.

**Bioactivity of Monoglycosylated Bartolosides.** Compounds **1** and **5**–**11** were evaluated for their cytotoxic activity against three different human cancer cell lines, namely, MG-63 (bone osteosarcoma), RKO (colon carcinoma), and T-47D (mammary gland ductal carcinoma). The bartolosides were considered inactive ( $IC_{50} > 10 \mu M$ ) against all tested cell lines. For compounds **1** and **5** we were able to determine  $IC_{50}$  values of 22 and 39  $\mu M$  against MG-63 cells, 40 and 40  $\mu M$  against RKO cells, and 23 and 22  $\mu M$  against T-47D cells, respectively, and exposure to **9** revealed an  $IC_{50}$  of 59.8  $\mu M$  in the assay with the T-47D cell line.

## CONCLUSION

Our report on the structures of seven new bartolosides provides a framework for the future structure elucidation of related compounds. The structures and the biosynthesis of the monoglycosylated bartolosides in *S. salina* LEGE 06099 bring up important questions regarding the function of the encoded glycosyltransferases and the potential involvement of odd-chain fatty acyl derivatives. Notably, the likely role of the putative halogenase BrtJ in carrying out a selective midchain dichlorination adds to the different types of halogenation that have been hypothesized for this still uncharacterized group of enzymes. Apparently, the bartolosides do not have strong bioactive

properties; however, their high abundance inside the cells suggests that these may have a fundamental biological role, which we intend to further investigate.

## EXPERIMENTAL SECTION

**General Experimental Procedures.** Optical rotations were measured on a Jasco P-2000 polarimeter (average of 10 measurements, 589 nm) using a 1 mL sample cell, with the exception of the optical rotation of **1** in MeCN, which was measured on an ADP410 polarimeter (Bellingham + Stanley Ltd.), also at 589 nm. UV–vis spectra were acquired on a Synergi HT microplate reader (BioTek) equipped with a Take 3 plate and a quartz cuvette. IR spectra were collected on a Jasco FT/IR 460 Plus spectrometer. NMR data were acquired in the indicated solvents in either a 400 MHz Bruker Avance III or a 600 MHz Bruker Avance III equipped with a 5 mm cryoprobe. Selective 1D TOCSY experiments were carried out with a magnetic susceptibility-matched (DMSO) NMR tube (Shigemi). Acquisition of NMR data for **1** isolated from *Nodosilena* sp. LEGE 06102 was detailed previously.<sup>5</sup> HRESIMS<sup>n</sup> data of pure compounds were acquired on an LTQ Orbitrap XL spectrometer, controlled by LTQ Tune Plus 2.5.5 and Xcalibur 2.1 (Thermo Scientific). The capillary voltage of the ESI was set to –3000 V. The capillary temperature was 300 °C. The sheath gas flow rate (nitrogen) was set to 5 (arbitrary unit as provided by the software settings). The capillary voltage was –48 V and the tube lens voltage –247.79 V. Samples were injected at a concentration of 50  $\mu g/mL$ . Selected ions were fragmented using collision-induced dissociation (CID) with a normalized collision energy of 40%. For the HRESIMS<sup>2</sup> chiral recognition analysis used to determine xylose configuration, the same instrument was used, but with an ESI capillary voltage of 3100 V, capillary temperature of 275 °C, capillary voltage of 42 V, and tube lens voltage of 85 V. Selected ions were fragmented using CID with a normalized collision energy of 30%. The maximum injection time for the MS<sup>n</sup> analysis and isolation width were found to be optimal for this analysis at 50 ms and 4.0  $m/z$ , respectively.

LC-HRESIMS profiles of extracts from *S. salina* LEGE 06099 and *S. salina* LEGE 06155 were acquired in an Accela HPLC coupled to an Accela PDA detector, Accela autosampler, and Accela 600 pump and to an LTQ Orbitrap XL spectrometer that was operated in negative ion mode under the conditions described above for HRESIMS<sup>n</sup> analysis. Analytical and semipreparative-scale HPLC purifications were carried out using a Waters 1525 binary pump, coupled to a Waters 2487 detector (monitored wavelengths: 230 and 275 nm).

All solvents used were MS-grade or HPLC-gradient grade for MS-based experiments, HPLC gradient for HPLC analysis/purification, and ACS grade for extraction, VLC, flash, and gravity column chromatographies. NMR solvents were acquired from either Sigma-Aldrich or BDH Prolabo (VWR).

**Cyanobacterial Strains.** *Synechocystis salina* LEGE 06099 and *S. salina* LEGE 06155 were obtained from the LEGE Culture Collection and grown at 25 °C, under a 14:10 h light (~30  $\mu mol$  photons  $m^{-2} s^{-1}$ )/dark regimen, in Z8 medium<sup>22</sup> supplemented with 25 g  $L^{-1}$  NaCl and 20  $\mu g L^{-1}$  vitamin B<sub>12</sub>.

**Extraction and Isolation.** Multiple cultures of *S. salina* LEGE 06099 were carried out in 6 L glass flasks with 4 L of medium. Biomass from a total of 120 L of culture was centrifuged (4500g, 10 min), rinsed with deionized H<sub>2</sub>O, harvested by another round of centrifugation, and freeze-dried to yield 15.3 g (d.w.). The biomass was extracted by repeated percolation with a warm mixture of CH<sub>2</sub>Cl<sub>2</sub>/MeOH (2:1, v/v). The resulting extract (2.6 g) was fractionated by normal-phase (Si gel 60, 0.015–0.040 mm, Merck KGaA) VLC using a gradient of increasing polarity from hexanes to EtOAc to MeOH, which yielded nine fractions (A–I). Fraction F, eluting with 4:1 EtOAc/MeOH (v/v), caused a marked reduction (>80%) in the viability of human cancer cell lines RKO, MG-63, and T-47D, when tested at 100  $\mu g/mL$  (Cytotoxicity Assays subsection), and was further fractionated by gravity column chromatography using Si gel 60 (0.040–0.063 mm, Merck KGaA) as stationary phase and a gradient of increasing polarity from 3:7 EtOAc/Hex (v/v) to EtOAc to 1:4 MeOH/EtOAc (v/v). The resulting subfractions were pooled according to their TLC profiles, and two



adjacent subfractions (F5 and F6), eluting with 2:3 EtOAc/Hex (v/v), contained the previously observed activity toward human cancer cell lines. Following semipreparative HPLC separations of each of the subfractions F5 (isocratic, 87% MeCN(aq), 3 mL/min, on a Synergi Fusion-RP column, 250 × 10 mm, 10 μm) and F6 (85% MeCN(aq) to 100% MeCN linear gradient over 25 min, 3 mL/min, on a Synergi Fusion-RP column, 250 × 10 mm, 10 μm, Phenomenex), compound 1 was isolated as the main component in both subfractions (30.4 mg,  $t_R$  = 28.5 min and 12.8 mg,  $t_R$  = 21.3 min, respectively, total 43.2 mg, 0.28% d.w.). The aforementioned HPLC separation of subfraction F6 also yielded a fraction ( $t_R$  = 15.0–16.7 min) with  $^1\text{H}$  NMR signals that could correspond to a bartolosiide-like compound and was subjected to analytical-scale HPLC separation (isocratic, 70% MeCN(aq), 1 mL/min, on a Synergi Fusion-RP column, 250 × 4.6 mm, 4 μm, Phenomenex) to yield pure 5 (0.5 mg, 0.003% d.w.,  $t_R$  = 39.6 min).

To obtain sufficient amounts of the minor halogenated compounds present in the cells of *S. salina* LEGE 06099 for structure elucidation, large-scale culturing of the cyanobacterium was carried out to yield 28.3 g of biomass (d.w.), after harvesting by centrifugation and freeze-drying. Following organic extraction and VLC (performed as above), fraction F contained  $^1\text{H}$  NMR signals consistent with bartolosiide-like metabolites and was further fractionated using gravity column chromatography as detailed above. Subfractions F3, F4, and F5 contained bartolosiide-like  $^1\text{H}$  NMR signals. Subfraction F3 was then fractionated using semipreparative HPLC using a Synergi Hydro-RP column (10 μm, 250 × 10 mm, Phenomenex). The elution was carried out at 3 mL/min and consisted initially of isocratic conditions (87% MeCN, aqueous) for 30 min, followed by a 5 min gradient to reach 100% MeCN, which was held for an additional 25 min. This afforded pure 1 (47.5 mg, 0.17% d.w.,  $t_R$  = 26.5 min), 6 (2.6 mg, 0.009% d.w.,  $t_R$  = 34.2 min), 7 (3.1 mg, 0.011% d.w.,  $t_R$  = 38.0 min), and 8 (4.4 mg, 0.016% d.w.,  $t_R$  = 38.5 min), as well as subfraction F3\_3 (0.7 mg,  $t_R$  = 24.0 min), which contained a bartolosiide-like metabolite (from  $^1\text{H}$  NMR analysis) among other components. The latter HPLC subfraction was subjected to analytical-scale HPLC purification under isocratic conditions (90% aqueous MeCN, 1 mL/min) using a Synergi Hydro-RP column (4 μm, 250 × 4.6 mm, Phenomenex) to afford 10 (0.2 mg, 0.0007% d.w.,  $t_R$  = 7.5 min). Subfractions F4 and F5 (from gravity column chromatography) were pooled based on an identical  $^1\text{H}$  NMR profile and were also further processed by semipreparative HPLC using a Synergi Fusion-RP column (10 μm, 250 × 10 mm, Phenomenex) and an elution program with a flow of 3 mL/min consisting of isocratic conditions for 30 min with 86% MeCN(aq), followed by a 5 min gradient to 100% MeCN, and these conditions were held for an additional 25 min. The procedure yielded pure 1 (116.5 mg, 0.41% d.w.,  $t_R$  = 19.5 min), 11 (5.4 mg, 0.019% d.w.,  $t_R$  = 40.5 min), and a fraction that also contained bartolosiide-like  $^1\text{H}$  NMR signals, but that required further purification. This was carried out under analytical-scale, isocratic HPLC conditions (77% aqueous MeCN, 1.2 mL/min) using a Synergi Fusion-RP column (4 μm, 250 × 10 mm, Phenomenex) to afford 9 (0.48 mg, 0.0017% d.w.,  $t_R$  = 35.0 min).

**Bartolosiide A (1):** white, glassy solid;  $[\alpha]_D^{20}$  −31.2 (c 0.32, MeCN),  $[\alpha]_D^{24}$  −25.4 (c 0.17,  $\text{CHCl}_3$ ); IR (thin film)  $\nu_{\max}$  3328, 2921, 2852, 1579, 1427, 1039  $\text{cm}^{-1}$ ;  $^1\text{H}$  and  $^{13}\text{C}$  NMR data, Table S1; HRESIMS  $m/z$  659.3838  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{36}\text{H}_{61}\text{Cl}_2\text{O}_6$ , 659.3851).

**Bartolosiide E (5):** white, glassy solid;  $[\alpha]_D^{20}$  +54 (c 0.008,  $\text{CHCl}_3$ ); IR (thin film)  $\nu_{\max}$  3413, 2919, 2850, 1585  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  (log  $\epsilon$ ) 209 (4.2), 228 (3.9), 259 (3.3), 299 (2.9) nm;  $^1\text{H}$  and  $^{13}\text{C}$  NMR, HMBC, and COSY data, Table 1; HRESIMS  $m/z$  631.3517  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{34}\text{H}_{57}\text{Cl}_2\text{O}_6$ , 631.3538).

**Bartolosiide F (6):** white, glassy solid;  $[\alpha]_D^{19}$  (not determined, measured value >3000); IR (thin film)  $\nu_{\max}$  3388, 2923, 2852, 1575, 1434, 1043  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  (log  $\epsilon$ ) 205 (3.3), 229 (3.6), 271 (3.0) nm;  $^1\text{H}$  and  $^{13}\text{C}$  NMR data, Table 2; HRESIMS  $m/z$  673.4002  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{37}\text{H}_{63}\text{Cl}_2\text{O}_6$ , 673.4007).

**Bartolosiide G (7):** white, glassy solid;  $[\alpha]_D^{21}$  −2.1 (c 0.12,  $\text{CHCl}_3$ ); IR (thin film)  $\nu_{\max}$  3403, 2921, 2850, 1457, 1041  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  (log  $\epsilon$ ) 205 (3.3), 229 (3.6), 272 (3.0) nm;  $^1\text{H}$ ,  $^{13}\text{C}$  NMR data,

Table 2; HRESIMS  $m/z$  625.4239  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{36}\text{H}_{62}\text{ClO}_6$ , 625.4240).

**Bartolosiide H (8):** white, glassy solid;  $[\alpha]_D^{21}$  +0.9 (c 0.22,  $\text{CHCl}_3$ ); IR (thin film)  $\nu_{\max}$  3392, 2923, 2852, 1428, 1041  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  (log  $\epsilon$ ) 205 (3.3), 229 (3.6), 271 (3.1) nm;  $^1\text{H}$  and  $^{13}\text{C}$  NMR data, Table 2; HRESIMS  $m/z$  687.4160  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{38}\text{H}_{65}\text{Cl}_2\text{O}_6$ , 687.4164).

**Bartolosiide I (9):** white, glassy solid;  $[\alpha]_D^{21}$  +22.6 (c 0.016,  $\text{CHCl}_3$ ); IR (thin film)  $\nu_{\max}$  3419, 2923, 2854, 1049  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  (log  $\epsilon$ ) 202 (3.8), 207 (4.1), 272 (3.0) nm;  $^1\text{H}$  and  $^{13}\text{C}$  NMR, HMBC, and COSY data, Table 1; HRESIMS  $m/z$  693.3454  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{36}\text{H}_{60}\text{Cl}_3\text{O}_6$ , 693.3461).

**Bartolosiide J (10):** white, glassy solid;  $[\alpha]_D^{21}$  (not determined, measured value >300); IR (thin film)  $\nu_{\max}$  3397, 2971, 2921, 2859, 1054  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  203, 226, 272 nm (molar absorptivity not determined, very low concentration);  $^1\text{H}$  and  $^{13}\text{C}$  NMR data, Table 2; HRESIMS  $m/z$  597.3923  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{34}\text{H}_{58}\text{ClO}_6$ , 597.3927).

**Bartolosiide K (11):** white, glassy solid;  $[\alpha]_D^{21}$  −9.7 (c 0.24,  $\text{CHCl}_3$ ); IR (thin film)  $\nu_{\max}$  3370, 2923, 2852, 1585, 1455, 1428, 1041  $\text{cm}^{-1}$ ; UV (MeOH)  $\lambda_{\max}$  (log  $\epsilon$ ) 204 (2.8), 229 (3.1), 272 (2.6);  $^1\text{H}$  and  $^{13}\text{C}$  NMR data, Table 2; HRESIMS  $m/z$  645.3686  $[\text{M} - \text{H}]^-$  (calcd for  $\text{C}_{35}\text{H}_{59}\text{Cl}_2\text{O}_6$ , 645.3694).

**Sugar Configuration Analysis.** An MS chiral recognition approach was used to determine the configuration of the xylose moiety and establish the identity of compound 1 isolated from *S. salina* LEGE 06099. The protocol by Augusti and co-workers<sup>23</sup> was slightly modified, as xylose had not been used in that study. Briefly, 1:1 (v/v) aqueous MeOH solutions containing 2 mM D- or L-xylose (Sigma-Aldrich), 2 mM N-Ac-L-Tyr (Sigma-Aldrich), and 1 mM  $\text{CuSO}_4$  were injected onto the mass spectrometer, and the trimeric ions  $[\text{Cu}(\text{N-Ac-L-Tyr})_2(\text{D/L-Xyl})]^+$  were fragmented by CID. The average relative abundance of the dimeric ions  $[\text{Cu}(\text{N-Ac-L-Tyr})_2]^+$  and  $[\text{Cu}(\text{N-Ac-L-Tyr})(\text{D/L-Xyl})]^+$  observed in the HRESIMS<sup>2</sup> spectra was determined for 30 scans, so as to calculate the average relative abundance ratios  $R_D$  and  $R_L$  for each sugar ( $R_{D/L} = [\text{Cu}(\text{N-Ac-L-Tyr})_2]^+ / [\text{Cu}(\text{N-Ac-L-Tyr})(\text{D/L-Xyl})]^+$ ). A chiral discrimination factor of 1.18 ( $R_D/R_L$ ) was obtained. Finally, the  $R$  value obtained from a solution containing the hydrolyzed sugar from 1 instead of the xylose standard was also determined and compared to  $R_D$  and  $R_L$ . Hydrolysis of 1 (1.3 mg) had been carried out in 2 M HCl (1 mL) at 100 °C for 1 h. After solvent removal *in vacuo*, the residue was resuspended in 1.5 mL of deionized  $\text{H}_2\text{O}$  and washed twice with 1 mL of  $\text{Et}_2\text{O}$ . The aqueous layer was dried *in vacuo* and resuspended in 100 μL of deionized  $\text{H}_2\text{O}$  (~20 mM xylose, assuming complete hydrolysis).

**Primer Design and *brtCD* Amplification and Sequencing.** Degenerate primers brtC-385F (5' AATATGTGGCAYTCW-GCYTCRG 3') and brtD-596R (5' GCATCRGAAAGCATCCA 3') were designed to amplify a ~1200 bp fragment of the *brtCD* region (as expected from the *brt* gene cluster of *S. salina* LEGE 06155), by annealing to conserved regions in *brtC* and *brtD* homologues, respectively (Figure S8). To this end, alignments of BrtC and BrtD protein sequences that were available in GenBank were carried out using the Geneious alignment tool in the Geneious software package (Biomatters Limited), and strongly conserved regions identified in the alignments; the corresponding nucleotide sequences were then used to design the degenerate primers (Figure S8). Total genomic DNA (gDNA) from fresh pellets of *S. salina* LEGE 06099 or LEGE 06155 (positive control for PCR) was isolated using a commercial kit (Gram-negative bacteria protocol, PureLink genomic DNA mini kit, Invitrogen). PCR amplification using the isolated gDNAs as templates was then carried out with the Platinum Taq high-fidelity DNA polymerase (Invitrogen) and the two degenerate primers. A thermal cycling protocol composed of initial denaturing at 98 °C (30 s), followed by 35 cycles of denaturing (98 °C, 10 s), annealing (55 °C, 30 s), and elongation (72 °C, 60 s) steps and a final elongation step (72 °C, 7 min) was used. A fragment of the expected size was visualized in an agarose gel for both strains (Figure S8). The band corresponding to the amplicon from *S. salina* LEGE 06099 was excised and purified using a cleanup kit (Nucleospin Gel and PCR-Clean Up, Machery-Nagel).

Table 1. NMR Spectroscopic Data (<sup>1</sup>H 600 MHz, <sup>13</sup>C 150 MHz, DMSO-*d*<sub>6</sub>) for Compounds 5 and 9

bartoloside E (5)					bartoloside I (9)				
position	δ <sub>C</sub> type	δ <sub>H</sub> (J in Hz)	HMBC <sup>a</sup>	COSY	no.	δ <sub>C</sub> type	δ <sub>H</sub> (J in Hz)	HMBC <sup>a</sup>	COSY
1	156.2, C				1	156.2, C			
2	115.8, C				2	115.8, C			
3	155.6, C				3	155.6, C			
3-OH		8.99, s	2, 3		3-OH		9.00, d (2.7)	2, 3	
4	109.0, CH	6.29, s	2, 3, 6, 24	24	4	109.0, CH	6.29, s	2, 3, 6, 24	
5	140.3, C				5	140.3, C			
6	106.2, CH	6.31, s	1, 2, 4, 24	24	6	106.1, CH	6.31, s	1, 2, 4, 24	
7	101.8, CH	4.70, d (7.2)	1	8	7	101.8, CH	4.70, d (6.9)		8
8	73.3, CH	3.20, m	7, 9	7, 8-OH	8	73.3, CH	3.21, m	7	7, 8-OH
8-OH		5.16, d (5.1)	8, 9	8	8-OH		5.17, t (5.2)	8, 9	8
9	76.6, CH	3.20, m	8	9-OH	9	76.6, CH	3.20, m		9-OH
9-OH		5.04, d (3.3)		9	9-OH		5.04, d (2.8)	10	9
10	69.4, CH	3.35, m	8	10-OH, 11a, 11b	10	69.4, CH	3.35, m		10-OH, 11a, 11b
10-OH		5.01, d (4.9)	9, 11	10	10-OH		5.01, d (4.9)	11	10
11a	65.6, CH <sub>2</sub>	3.71, dd (11.2, 5.3)	7, 9, 10	10, 11b	11a	65.6, CH <sub>2</sub>	3.72, dd (11.3, 5.3)	7	10, 11b
11b		3.16, dd (~11.1)	7	10, 11a	11b		3.16, dd (~10.6)	9	10, 11a
12a	22.5, CH <sub>2</sub>	2.54, m	1, 2, 3, 13	12b, 13	12a	22.5, CH <sub>2</sub>	2.54, m	2	12b, 13
12b		2.46, m	1, 2, 3, 13	12a, 13	12b		2.47, m	2	12a, 13
13	28.8, CH <sub>2</sub>	1.40, m		12a, 12b	13	28.7, CH <sub>2</sub>	1.40, m		12a, 12b
14	29.0–28.5, CH <sub>2</sub>	1.29–1.24, m	15, 16		14	29.0–28.3, CH <sub>2</sub>	1.30–1.24, m		
15a	26.0–25.6, CH <sub>2</sub>	1.45–1.43, m		15b, 16a, 16b	15a	25.9–25.6, CH <sub>2</sub>	1.45–1.43, m		15b, 16a, 16b
15b		1.36–1.34, m		15a, 16a, 16b	15b		1.36–1.34, m	14	15a, 16a, 16b
16a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m		15a, 15b, 16b, 17	16a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m		15a, 15b, 16b, 17
16b		1.63–1.60, m	17	15a, 15b, 16a, 17	16b		1.63–1.60, m	17	15a, 15b, 16a, 17
17	64.9–64.8, CH	4.01, m		16a, 16b, 18a, 18b	17	64.9, CH	4.01, m		16a, 16b, 18a, 18b
18a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m		17, 18b, 19a, 19b	18a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m		17, 18b, 19a, 19b
18b		1.63–1.60, m	17	17, 18a, 19a, 19b	18b		1.63–1.60, m	17	17, 18a, 19a, 19b
19a	26.0–25.6, CH <sub>2</sub>	1.45–1.43, m		18a, 18b, 19b	19a	25.9–25.6, CH <sub>2</sub>	1.45–1.43, m		18a, 18b, 19b
19b		1.36–1.34, m	22	18a, 18b, 19a	19b		1.36–1.34, m	20	18a, 18b, 19a
20	29.0–28.5, CH <sub>2</sub>	1.29–1.24, m	18, 19, 21, 22, 23		20	29.0–28.3, CH <sub>2</sub>	1.30–1.24, m	21	
21	30.7, CH <sub>2</sub>	1.25, m	22, 23		21	30.7, CH <sub>2</sub>	1.30, m	20, 22	23
22	22.0, CH <sub>2</sub>	1.28, m	19, 20, 21, 23	23	22	22.0–21.9, CH <sub>2</sub>	1.28, m	23	23
23	13.9, CH <sub>3</sub>	0.86, t (6.9)	21, 22	22	23	13.9–13.8, CH <sub>3</sub>	0.86, t (7.2)	21, 22	21, 22
24	35.1, CH <sub>2</sub>	2.40, t (7.7)	4, 5, 6, 25, 26	4, 6, 25	24	35.1, CH <sub>2</sub>	2.40, m	4, 5, 6, 25	25
25	30.7, CH <sub>2</sub>	1.49, m	24, 26	24, 26	25	30.6, CH <sub>2</sub>	1.50, m	26	24, 26
26	28.3, CH <sub>2</sub>	1.27, m	25, 27, 28	25	26	28.2 <sup>b</sup> , CH <sub>2</sub>	1.31, m		25, 27
27	29.0–28.5, CH <sub>2</sub>	1.29–1.24, m	25, 26, 28, 29		27	24.8–24.5, CH <sub>2</sub>	1.57, m	26, 28, 30	26, 28
28a	26.0–25.6, CH <sub>2</sub>	1.45–1.43, m		28b, 29a, 29b	28	47.2–47.1, CH <sub>2</sub>	2.19, m	27, 29, 30, 31	27
28b		1.36–1.34, m		28a, 29a, 29b	29	97.2, C			
29a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m		28a, 28b, 29b, 30	30	47.2–47.1, CH <sub>2</sub>	2.19, m	27, 28, 29, 31	31
29b		1.63–1.60, m	30	28a, 28b, 29a, 30	31	24.8–24.5, CH <sub>2</sub>	1.57, m	28, 30	30
30	64.9–64.8, CH	4.01, m		29a, 29b, 31a, 31b	32	29.0–28.3, CH <sub>2</sub>	1.30–1.24, m	33	
31a	37.5, CH <sub>2</sub>	1.72–1.70, m		30, 31b	33	29.0–28.3, CH <sub>2</sub>	1.30–1.24, m	32	
31b		1.63–1.60, m	30	30, 31a	34	31.1, CH <sub>2</sub>	1.26, m	33	36
32a	28.1, CH <sub>2</sub>	1.41, m			35	22.0–21.9, CH <sub>2</sub>	1.28, m	36	36
32b		1.31, m			36	13.9–13.8, CH <sub>3</sub>	0.86, t (7.2)	34, 35	34, 35
33	21.7, CH <sub>2</sub>	1.28, m	31, 32, 34	34					
34	13.9, CH <sub>3</sub>	0.87, t (7.3)	32, 33	33					

<sup>a</sup>From proton to the indicated carbon. <sup>b</sup>From HSQC-TOCSY data.

Table 2. NMR Spectroscopic Data (DMSO- $d_6$ ) for Compounds 6–8 ( $^1\text{H}$  400 MHz,  $^{13}\text{C}$  100 MHz), 10, and 11 ( $^1\text{H}$  600 MHz,  $^{13}\text{C}$  150 MHz)

bartolosiide F (6)				bartolosiide G (7)				bartolosiide H (8)				bartolosiide J (10)				bartolosiide K (11)			
position	$\delta_{\text{C}}$ , type	$\delta_{\text{H}}$ (J in Hz)	position	$\delta_{\text{C}}$ , type	$\delta_{\text{H}}$ (J in Hz)	position	$\delta_{\text{C}}$ , type	$\delta_{\text{H}}$ (J in Hz)	position	$\delta_{\text{C}}$ , type	$\delta_{\text{H}}$ (J in Hz)	position	$\delta_{\text{C}}$ , type	$\delta_{\text{H}}$ (J in Hz)	position	$\delta_{\text{C}}$ , type	$\delta_{\text{H}}$ (J in Hz)		
1	156.2, C		1	156.2, C		1	156.2, C		1	156.2, C		1	156.2, C		1	156.2, C			
2	115.8, C		2	115.8, C		2	115.8, C		2	115.8, C		2	115.8, C		2	115.8, C			
3	155.5, C		3	155.5, C		3	155.5, C		3	155.5, C		3	155.5, C		3	155.6, C			
3-OH		8.97, s	3-OH		8.97, s	3-OH		8.97, s	3-OH		8.97, s	3-OH		8.99, s	3-OH		8.99, s		
4	109.0, CH	6.29, d (1.2)	4	109.0, CH	6.29, d (1.4)	4	109.0, CH	6.29, d (1.3)	4	109.0, CH	6.28, s	4	109.0, CH	6.28, s	4	109.0, CH	6.29, s		
5	140.3, C		5	140.3, C		5	140.3, C		5	140.3, C		5	141.0, C		5	140.3, C			
6	106.2, CH	6.31, d (1.3)	6	106.2, CH	6.31, d (1.5)	6	106.2, CH	6.31, d (1.4)	6	106.2, CH	6.31, d (1.4)	6	105.9, CH	6.31, s	6	106.1, CH	6.31, s		
7	101.8, CH	4.71, d (7.2)	7	101.8, CH	4.70, d (7.2)	7	101.8, CH	4.70, d (7.2)	7	101.8, CH	4.70, d (7.3)	7	101.5, CH	4.70, d (6.9)	7	101.8, CH	4.70, d (6.8)		
8	73.3, CH	3.21, m	8	73.3, CH	3.21, m	8	73.3, CH	3.21, m	8	73.3, CH	3.21, m	8	73.0, CH	3.20, m	8	73.3, CH	3.21–3.20, m		
8-OH		5.14, d (5.4)	8-OH		5.14, d (5.4)	8-OH		5.14, d (5.5)	8-OH		5.14, d (5.5)	8-OH		5.17, d (4.8)	8-OH		5.16, d (4.8)		
9	76.6, CH	3.21, m	9	76.6, CH	3.20, m	9	76.6, CH	3.21, m	9	76.6, CH	3.20, m	9	76.2, CH	3.20, m	9	76.6, CH	3.21–3.20, m		
9-OH		5.02, d (4.5)	9-OH		5.02, d (4.6)	9-OH		5.02, d (4.5)	9-OH		5.02, d (4.5)	9-OH		5.05, d (3.9)	9-OH		5.04, d (3.5)		
10	69.4, CH	3.36, m	10	69.4, CH	3.35, m	10	69.4, CH	3.35, m	10	69.4, CH	3.35, m	10	69.1, CH	3.35, m	10	69.4, CH	3.35, m		
10-OH		4.99, d (5.0)	10-OH		4.99, d (5.0)	10-OH		4.99, d (5.0)	10-OH		4.99, d (4.9)	10-OH		5.01, d (4.9)	10-OH		5.01, d (4.9)		
11a	65.6, CH <sub>2</sub>	3.72, dd (11.2, 5.2)	11a	65.6, CH <sub>2</sub>	3.72, dd (11.2, 5.2)	11a	65.6, CH <sub>2</sub>	3.72, dd (11.2, 5.2)	11a	65.6, CH <sub>2</sub>	3.72, dd (11.2, 5.2)	11a	65.4, CH <sub>2</sub>	3.71, dd (11.2, 5.2)	11a	65.6, CH <sub>2</sub>	3.71, dd (11.2, 5.2)		
11b		3.16, dd (~10.6)	11b		3.16, dd (~10.4)	11b		3.16, dd (~10.4)	11b		3.17, dd (~10.7)	11b		3.16, dd (~11.0)	11b		3.16, dd (~10.8)		
12a	22.5, CH <sub>2</sub>	2.54, m	12a	22.5, CH <sub>2</sub>	2.54, m	12a	22.5, CH <sub>2</sub>	2.54, m	12a	22.5, CH <sub>2</sub>	2.54, m	12	22.5, CH <sub>2</sub>	2.55, m	12a	22.5, CH <sub>2</sub>	2.54, m		
12b		2.48, m	12b		2.47, m	12b		2.47, m	12b		2.48, m	12b		2.48, m	12b		2.47, m		
13	28.7, CH <sub>2</sub>	1.40, m	13	28.8, CH <sub>2</sub>	1.40, m	13	28.8, CH <sub>2</sub>	1.40, m	13	28.8, CH <sub>2</sub>	1.40, m	13	28.4, CH <sub>2</sub>	1.40, m	13	29.0–28.2, CH <sub>2</sub>	n.d. <sup>d</sup>		
14	29.0–28.1, CH <sub>2</sub>	1.30–1.23, m	14	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	14	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m	14	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m	14	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	14	29.0–28.2, CH <sub>2</sub>	1.29–1.23, m		
15a	25.9–25.5, CH <sub>2</sub>	1.46–1.44, m	15a	25.9 <sup>b</sup> , CH <sub>2</sub>	1.45, m	15a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	15a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	15a	25.5, CH <sub>2</sub>	1.46, m	15a	26.0–25.6, CH <sub>2</sub>	1.47–1.41, m		
15b		1.37–1.35, m	15b		1.35, m	15b		1.35, m	15b		1.37–1.35, m	15b		1.35, m	15b		1.37–1.33, m		
16a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	16a	37.9–37.8, CH <sub>2</sub>	1.70, m	16a	37.9–37.8, CH <sub>2</sub>	1.70, m	16a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	16a	37.5, CH <sub>2</sub>	1.71, m	16a	37.9–37.8, CH <sub>2</sub>	1.71–1.70, m		
16b		1.63–1.60, m	16b		1.62, m	16b		1.62, m	16b		1.63–1.61, m	16b		1.61, m	16b		1.62–1.60, m		
17	64.8, CH	4.01, m	17	64.8, CH	4.00, t (8.6, 4.3)	17	64.8, CH	4.01, m	17	64.9–64.8, CH	4.01, m	17	64.6, CH	4.00, m	17	64.9–64.8, CH	4.01, m		
18a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	18a	37.9–37.8, CH <sub>2</sub>	1.70, m	18a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	18a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	18a	37.5, CH <sub>2</sub>	1.71, m	18a	37.9–37.8, CH <sub>2</sub>	1.71–1.70, m		
18b		1.63–1.60, m	18b		1.62, m	18b		1.62, m	18b		1.63–1.61, m	18b		1.61, m	18b		1.62–1.60, m		
19a	25.9–25.5, CH <sub>2</sub>	1.46–1.44, m	19a	25.5 <sup>b</sup> , CH <sub>2</sub>	1.45, m	19a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	19a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	19a	25.5, CH <sub>2</sub>	1.46, m	19a	26.0–25.6, CH <sub>2</sub>	1.47–1.41, m		
19b		1.37–1.35, m	19b		1.35, m	19b		1.35, m	19b		1.37–1.35, m	19b		1.35, m	19b		1.37–1.33, m		
20	29.0–28.1, CH <sub>2</sub>	1.30–1.23, m	20	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	20	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m	20	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m	20	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	20	29.0–28.2, CH <sub>2</sub>	1.29–1.23, m		
21	30.7, CH <sub>2</sub>	1.28, m	21	30.7, CH <sub>2</sub>	1.26, m	21	30.7, CH <sub>2</sub>	1.26, m	21	30.7, CH <sub>2</sub>	1.27, m	21	30.7–30.5, CH <sub>2</sub>	1.25, m	21	30.7, CH <sub>2</sub>	1.29–1.23, m		
22	22.0, CH <sub>2</sub>	1.26, m	22	22.1–22.0, CH <sub>2</sub>	1.26, m	22	22.1–22.0, CH <sub>2</sub>	1.26, m	22	22.1–22.0, CH <sub>2</sub>	1.26, m	22	21.7, CH <sub>2</sub>	1.26, m	22	22.0, CH <sub>2</sub>	1.29–1.23, m		
23	13.9–13.8, CH <sub>3</sub>	0.86, t (7.0)	23	13.9–13.8, CH <sub>3</sub>	0.86–0.85, t (7.0)	23	13.9–13.8, CH <sub>3</sub>	0.86–0.85, t (7.0)	23	13.9–13.8, CH <sub>3</sub>	0.86, t (6.9)	23	13.6, CH <sub>3</sub>	0.86–0.85, t (6.9)	23	13.9, CH <sub>3</sub>	0.86, t (6.9)		
24	35.1, CH <sub>2</sub>	2.40, t (7.6)	24	35.2, CH <sub>2</sub>	2.39, t (7.6)	24	35.1, CH <sub>2</sub>	2.40, t (7.5)	24	35.1, CH <sub>2</sub>	2.40, t (7.5)	24	34.9, CH <sub>2</sub>	2.40 <sup>c</sup> , m	24	35.2, CH <sub>2</sub>	2.39, t (7.6)		
25	30.6, CH <sub>2</sub>	1.50, m	25	30.7, CH <sub>2</sub>	1.49, m	25	30.6, CH <sub>2</sub>	1.50, m	25	30.6, CH <sub>2</sub>	1.50, m	25	30.5, CH <sub>2</sub>	1.48, m	25	30.7, CH <sub>2</sub>	1.50–1.49, m		
26	29.0–28.1, CH <sub>2</sub>	1.30, m	26	29.0–28.4, CH <sub>2</sub>	1.25*, m	26	29.0–28.1, CH <sub>2</sub>	1.28, m	26	29.0–28.1, CH <sub>2</sub>	1.28, m	26	28.7–28.4, CH <sub>2</sub>	1.27, m	26	29.0–28.2, CH <sub>2</sub>	1.29–1.23, m		
27a	25.9–25.5, CH <sub>2</sub>	1.46–1.44, m	27	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	27a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	27a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	27	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	27a	26.0–25.6, CH <sub>2</sub>	1.47–1.41, m		
27b		1.37–1.35, m	28	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	27b	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	28	28.7–28.4, CH <sub>2</sub>	1.37–1.35, m	28	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	27b	28.7–28.4, CH <sub>2</sub>	1.37–1.33, m		
28a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	29	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	28a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	29	28.7–28.4, CH <sub>2</sub>	1.72–1.70, m	29	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	28a	37.9–37.8, CH <sub>2</sub>	1.71–1.70, m		



Table 2. continued

bartoloseide F (6)				bartoloseide G (7)				bartoloseide H (8)				bartoloseide J (10)				bartoloseide K (11)			
position	$\delta_C$ , type	$\delta_H$ (J in Hz)	position	$\delta_C$ , type	$\delta_H$ (J in Hz)	position	$\delta_C$ , type	$\delta_H$ (J in Hz)	position	$\delta_C^a$ , type	$\delta_H$ (J in Hz)	position	$\delta_C$ , type	$\delta_H$ (J in Hz)	position	$\delta_C$ , type	$\delta_H$ (J in Hz)		
28b		1.63–1.60, m	30	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	28b		1.63–1.61, m	30	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	28b		1.62–1.60, m					
29	64.8, CH	4.01, m	31	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	29	64.9–64.8, CH	4.01, m	31	28.7–28.4, CH <sub>2</sub>	1.29–1.23, m	29	64.9–64.8, CH	4.01, m					
30a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	32	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	30a	37.9–37.8, CH <sub>2</sub>	1.72–1.70, m	32	30.7–30.5, CH <sub>2</sub>	1.25, m	30a	37.9–37.8, CH <sub>2</sub>	1.71–1.70, m					
30b		1.63–1.60, m	33	29.0–28.4, CH <sub>2</sub>	1.29–1.23, m	30b		1.63–1.61, m	33	21.7, CH <sub>2</sub>	1.26, m	30b		1.62–1.60, m					
31a	25.9–25.5, CH <sub>2</sub>	1.46–1.44, m	34	31.3, CH <sub>2</sub>	1.24, m	31a	25.9–25.5, CH <sub>2</sub>	1.46–1.43, m	34	13.6, CH <sub>3</sub>	0.86–0.85, t (6.9)	31a	26.0–25.6, CH <sub>2</sub>	1.47–1.41, m					
31b		1.37–1.35, m	35	22.1–22.0, CH <sub>2</sub>	1.26, m	31b		1.37–1.35, m				31b		1.37–1.33, m					
32	29.0–28.1, CH <sub>2</sub>	1.30–1.23, m	36	13.9–13.8, CH <sub>3</sub>	0.86–0.85, t (7.0)	32	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m				32	29.0–28.2, CH <sub>2</sub>	1.29–1.23, m					
33	29.0–28.1, CH <sub>2</sub>	1.30–1.23, m				33	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m				33	31.1, CH <sub>2</sub>	1.29–1.23, m					
34	29.0–28.1, CH <sub>2</sub>	1.30–1.23, m				34	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m				34	22.0, CH <sub>2</sub>	1.29–1.23, m					
35	31.2, CH <sub>2</sub>	1.25, m				35	29.0–28.1, CH <sub>2</sub>	1.29–1.23, m				35	13.9, CH <sub>3</sub>	0.86, t (6.9)					
36	22.0, CH <sub>2</sub>	1.26, m				36	31.2, CH <sub>2</sub>	1.25, m											
37	13.9–13.8, CH <sub>3</sub>	0.86, t (7.0)				37	22.1–22.0, CH <sub>2</sub>	1.26, m											
						38	13.9–13.8, CH <sub>3</sub>	0.86, t (6.9)											

<sup>a</sup>Extracted from HSQC data (for CH, CH<sub>2</sub>, and CH<sub>3</sub> carbon types) or HMBC data (for C carbon type). <sup>b</sup>From HSQC-TOCSY. <sup>c</sup>Signal partially obscured. <sup>d</sup>n.d., not determined.

<sup>a</sup>Extracted from HSQC data (for CH, CH<sub>2</sub>, and CH<sub>3</sub> carbon types) or HMBC data (for C carbon type). <sup>b</sup>From HSQC-TOCSY. <sup>c</sup>Signal partially obscured. <sup>d</sup>n.d., not determined.

The purified amplicon was ligated to a pGEM-T Easy Vector (Promega) using T4 DNA ligase and the resulting construct was cloned onto chemically competent *E. coli* TOP10 cells (Life Technologies), purified from a 5 mL culture of transformed *E. coli* cells (GenElute plasmid miniprep kit, Sigma-Aldrich), and sequenced using M13 primers by Sanger Technology (GATC Biotech). The resulting sequence showed high similarity (82% identity) to a portion of the *brtCD* region from *S. salina* LEGE 06155.<sup>5</sup>

**Genome Sequencing, Identification, and Annotation of the *brt* Gene Cluster.** Total genomic DNA was isolated from a fresh pellet of a *S. salina* LEGE 06099 culture using a CTAB-chloroform/isoamyl alcohol-based protocol.<sup>24</sup> The gDNA was first fragmented using the AB Library Builder System (Applied Biosystems) and subsequently submitted for sequencing on the Ion Torrent PGM (ThermoFisher Scientific) platform. After sequencing, the reads were evaluated for quality using FastQC<sup>25</sup> followed by assembling with SPAdes version 3.7.0.<sup>26</sup> Using the BLAST algorithm and the Geneious software package, the generated contigs were queried with the PCR-derived *brtCD* sequence obtained from *S. salina* LEGE 06099 (see above), which was found (100% identity) within a 106.5 kb contig. The genomic context of these genes was annotated manually, by using the predicted ORFs as queries in blast searches against the NCBI nucleotide and protein databases (Table S2). The boundaries of the *brt* gene cluster were defined by the high similarity of flanking genes to the genomes of the closely related *Synechocystis* sp. strains PCC 6803 and PCC 6714 (Table S2). The annotated nucleotide data have been deposited in GenBank under accession number KX083339.

**Cytotoxicity Assays.** The evaluation of the cytotoxic activity of chromatographic fractions and pure compounds was performed on the human cancer cell lines T47D (breast carcinoma cells), RKO (colon carcinoma cells), and MG-63 (osteosarcoma cells) at 30  $\mu$ g/mL (fractions) or dilutions from 50 to 0.003  $\mu$ g/mL (pure compounds). IC<sub>50</sub> values were determined from dose–response curves using the software GraphPad Prism v6.0 (GraphPad Software). Cells were cultured in Dulbecco's modified Eagle medium (DMEM Glutamax, Gibco), supplemented with 10% (v/v) fetal bovine serum (Gibco), 2.5  $\mu$ g/mL fungizone (Gibco), 100 IU/mL penicillin, and 100  $\mu$ g/mL streptomycin (Pen.Step, Gibco). Cells were preinoculated for 24 h (37 °C; 5% CO<sub>2</sub>) in 96-well plates at a concentration of 3.3  $\times$  10<sup>4</sup> cells/mL for cell adhesion. An exposure to the fractions and compounds was then carried out for 48 h. For the determination of cell viability, exposed cells were incubated for 3 h with 0.5 mg/mL MTT, and the resulting purple-colored formazan salts were dissolved in 100  $\mu$ L of DMSO. The absorbance was measured at 550 nm in a microplate reader (Synergi HT, Biotek). All tests were run in triplicate and averaged.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jnatprod.6b00351.

NMR data for 1, NMR spectra for all compounds, annotated HRESIMS<sup>n</sup> data, phylogenetic analysis of the cyanobacterium strain, details on primer design, and annotation of the *brt* gene cluster (PDF)

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### Notes

The authors declare no competing financial interest.

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